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Analysis

The livestock sector and planetary boundaries: A 'limits to growth' perspective with dietary implications

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ABSTRACT

The livestock sector is a key driver of humanity's transgression of several planetary boundaries, with the production of ruminant meat being particularly impactful. Given current trends in demand for animal products, strategies to significantly reduce the livestock sector's environmental impacts are urgently needed. Here we draw on published data to examine livestock's impacts in three key critical sustainability domains within the planetary boundaries framework – climate change, biochemical flows and land-system change, and seek to quantify livestock's occupation of humanity's safe operating space now and into the future (2050). We estimate that the livestock sector may already occupy the majority of, or transgress, humanity's safe operating space across these domains, with such impacts forecast to grow by 2050. Furthermore, we explore the potential of reasonably foreseeable technological measures to mitigate the sector's environmental impacts. While such measures are deemed necessary, their effects are unlikely to be sufficient to shrink the scale of livestock's impacts to a sustainable level, as defined by the three planetary boundaries tested. The implication of these findings is that macroeconomic policies promoting both sustainable production and consumption practices are integral to the realisation of a sustainable food system, where humanity functions within its safe operating space.

1. Introduction

The notion of limits to growth emerged primarily to critique the global growth-orientated economic system, which is argued exceeds the planet's carrying capacity and therefore is unsustainable (Victor, 2010; Daly, 1992; Costanza et al., 1997; Jackson, 2009). While the original limits to growth thesis gave primacy to natural resource scarcity and the capacity of ecosystems to absorb pollution (Meadows, 1972), focus has since shifted to specific environmental domains that impact the global climatic system and Earth-system functioning. This new approach is captured by the work on planetary boundaries, a framework that arguably represents the most scientifically robust means of quantifying planetary environmental constraints, or a 'safe operating space' for humanity. The boundaries refer to nine interrelated domains including two core boundaries, climate change and biosphere integrity, designated as such due to their fundamental importance to the Earth-system (Steffen et al., 2015).

Of the seven domains whose anthropogenic impacts are quantified with empirical data, four currently exceed values that define the planetary boundary - climate change, biosphere integrity, land-system change and biogeochemical flows (Steffen et al., 2015). This has in some respects confirmed concerns of ecological economists that the biophysical scale of anthropogenic impacts emanating from the global economy may be approaching critical sustainability thresholds. The transgression of such thresholds, where they exist, may cause abrupt or risky changes to the Earth-system (Steffen et al., 2015). Reducing impacts to a safe level, as defined by planetary boundaries, represents an important goal of global environmental governance. While the planetary boundaries framework has not been without criticism (see e.g. Montoya et al., 2018) – to which leading advocates have responded (Rockström et al., 2018) – the framework has become a touchstone of environmental analysis and receives broad support, even as it is acknowledged that sustainability is notoriously hard to measure and all attempts, necessarily, will be imperfect (Campbell et al., 2017; Springmann et al., 2018). Presently, the planetary boundaries framework is arguably the most robust conceptual lens available in terms of defining food system-specific absolute sustainability thresholds. In this paper we proceed on that basis.

The global food system is a key driver of anthropogenic impacts on the Earth-system (Foley et al., 2011): it is responsible for one-quarter of

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greenhouse gas (GHG) emissions (Poore and Nemecek, 2018); nearly nine-tenths of anthropogenic nitrogen mobilisation (Galloway et al., 2008); and nearly two-fifths of ice-free land-uses (Ramankutty et al., 2008). Food system impacts are driven substantially by livestock production, stemming largely from its resource demands with respect to land (Poore and Nemecek, 2018), energy (Goodland, 1997), water (Ran et al., 2016) and fertiliser (Liu et al., 2016) as well as GHG emissions from various stages of the production process (Herrero et al., 2016). These effects are highly heterogeneous across different regions and production systems; while ruminant production occupies 90% of livestock's total land area (Poore and Nemecek, 2018) and emits 80% of the sector's GHG emissions (FAO, 2017a), monogastric animals consume 76% of the human-edible feed globally (Mottet et al., 2017). Feed production is itself a significant driver of the sector's fertiliser and arable land use. The production of ruminant meat is particularly impactful in each of the domains considered here, in ways to be detailed below.

In return for these impacts, the livestock sector contributes one-quarter of human protein consumption and 18% of calories consumed globally (Mottet et al., 2017). The comparatively large environmental impact of livestock production is highly problematic in a sustainability sense. This is due to the relative scale of its impact in relation to its contribution to food security as well as the continuing growth in animal product consumption, in line with increasing affluence and urbanisation trends globally (Steinfeld et al., 2006; Seto and Ramankutty, 2016; Kearney, 2010). Such trends are highly non-linear across different world regions, with beef consumption tending to plateau in much of the developed world but continuing to grow rapidly in the developing world. Given the comparatively high environmental cost of ruminant production, such trends will continue to drive the sector's environmental impacts in the absence of successful mitigation strategies.

When the sector's anthropogenic impacts are viewed as production-orientated problems, solutions tend to focus on technologies that promote greater resource-use efficiency as a means of decoupling production from environmental impact (Asafu-Adjaye et al., 2015). This technological transition is said to optimise, and be optimised by, economic growth (Asafu-Adjaye et al., 2015), while correct prices signal which technologies are likely to best promote this end. This neoclassical approach to sustainability is pursued in the food system with the intensification of production, generally (Alexandratos and Bruinsma, 2012) and in the livestock sector (Steinfeld et al., 2006; Gerber et al., 2013).

While acknowledging that efficiency gains achieve relative decoupling, ecological economists tend to argue that such gains do not always or often achieve the critical sustainability imperative of absolute decoupling, or prevent aggregate impacts from transgressing planetary boundaries (Steffen et al., 2015). The demand response that efficiency gains tend to trigger is a crucial limiting factor to their utility - the so-called rebound effect (Alcott, 2005; Valin et al., 2013) - as well as the fact that such gains are pursued within a broader paradigm of economic growth that has historically correlated with more resource-intensive consumption (in the food sector and more generally). These effects may be evident in the widespread adoption of diets high in animal protein in more developed parts of the world, which contribute to the livestock sector's rising impacts in absolute terms. Ecological economists thus emphasise a need to look beyond the scope of production-orientated solutions and endorse a scale-based approach to environmental governance (Pelletier, 2010) - the ultimate aim of which is to constrain, in biophysical terms, the scale of anthropogenic impacts to a sustainable level.

The environmental impact of food production is increasingly coming under examination with respect to a number of planetary boundary domains (Campbell et al., 2017; Hadjikakou and Wiedmann, 2017; Springmann et al., 2018; Heck et al., 2018; Gordon et al., 2017). The present study examines the major impact the livestock sector has on three of these: climate change; biogeochemical flows and land-system change. After reviewing the latest evidence of livestock's impacts in relation to planetary boundaries, our primary aim is to understand the extent to which production-orientated measures can reduce pressure on sustainability boundaries as global animal protein demands continue to grow. Evidence reviewed suggests that such measures are unlikely to achieve the critical sustainability imperative represented by planetary boundaries. On that basis we consider some key dietary implications, with special focus on the importance of sustainable diets in an age of ecological limits. Herrero et al. (2016) notes that sustainable diets can be promoted via two principal means; (1) by directly targeting consumer preferences, and (2) by inducing change via the pricing system, principally through the introduction of taxes (Goodland, 1997; Springmann et al., 2016a). This study seeks to build on earlier contributions to method (2), while proposing a broader macroeconomic policy that is deemed to better align with the scale-based approach to environmental governance generally endorsed by ecological economists.

2. Methods

2.1. Overview

This study summarises the livestock sector's impact on three planetary boundary domains: climate change, biogeochemical flows and land-system change. The livestock sector includes the production of ruminant and monogastric meat, milk and eggs. Seafood is not included. The baseline year for the analysis is 2010 for climate change, and 2009 for biogeochemical flows and land-system change. Baseline values are projected into the future in two scenarios, a reference scenario and a scenario that incorporates gains in resource-use efficiency. Projections relate to 2050 to align with the temporal horizon of a number of studies that project important food system metrics into the future (Alexandratos and Bruinsma, 2012; Bajželj et al., 2014; Schader et al., 2015; Odegard and Van de Voet, 2014). This is followed by an analysis of the mitigation potential of simulated changes in demand arising from a hypothetical tax levied on livestock products. For purposes of validation we carry out a comprehensive comparison of our estimates with those from other studies. We conclude with a discussion of the dietary and macroeconomic implications of the results.

2.2. Selecting and setting values for planetary boundaries

The climate change, biogeochemical flows and land-system change boundaries were chosen principally because they each satisfy three conditions: first, food system impacts are significant, with the livestock sector being a major source of such impacts. Second, the sustainable boundary and baseline values are well researched and widely prominent in the literature. And third, baseline values defined by Steffen et al. (2015) surpass those defining humanity's safe operating space, putting each in a state of increasing or high risk of crossing a critical sustainability threshold. The other domain transgressing the sustainability boundary is biosphere integrity and despite evidence that it too is impacted materially by livestock production (Machovina et al., 2015; Campbell et al., 2017), it has been excluded from this study due to difficulties in quantifying such impacts. The biosphere integrity boundary does however place a constraint on the amount and pattern of land-system change in terrestrial biomes, particularly forests, and is therefore reflected in the land-system change boundary (Steffen et al., 2015). Table 1 provides a summary of literature quantifying the sustainability boundaries included here, and the values defining baseline impacts of the livestock sector and food system.

2.2.1. Climate change

The climate change boundary is defined by an emission budget of 20.1 gigatonnes of CO_2eq ($GtCO_2$eq) per annum. This level of emissions equates to a 'likely' or greater than 66% chance of limiting global

Table 1
Summary of planetary boundaries and control variable value sources.

Domain	Planetary boundary		Baseline values	
	Baseline	Literature	Livestock	Food system
Climate change	20.1 $GtCO_2eq$	Rogelj et al. (2011)	FAO (2017a)	FAO (2017b)
Biogeochemical flows	69 TgN	Springmann et al. (2018)	Davis et al. (2016)	Davis et al. (2016)
Land-system change	13.8 Mkm^2	Steffen et al. (2015)	Bajželj et al. (2014)	Bajželj et al. (2014)

warming to 2 degrees Celsius above pre-industrial temperatures, in line with Recommended Concentration Pathway (RCP) 2.6 (Rogelj et al., 2011). While other studies have downscaled this boundary for agriculture only (Springmann et al., 2018), here we retain the full boundary value for our main analysis. To define the livestock sector's baseline emissions, we rely on data from the FAO's GLEAM model. GLEAM adopts a life-cycle assessment for defining emission factors, which includes direct agricultural, direct and indirect energy and land-use change emissions (FAO, 2017a). Land-use change emissions are excluded from this analysis for two reasons. First, the carbon storage capacity of forest biomes forms part of the methodology that determines the land-system change boundary (Steffen et al., 2015). And second, the methodology by which baseline land-use emissions are defined is not a suitable basis upon which to project future projections.

2.2.2. Biogeochemical flows

This boundary refers to changes in biogeochemical flows other than carbon, primarily focusing on nitrogen (N) and phosphorus (P). Steffen et al. (2015) notes that although the nitrogen and phosphorus boundaries were developed independently, they are closely linked based on the N:P ratio is the growing plant tissue of agricultural crops and the concomitant ratio with which they are incorporated into synthetic fertilisers. Their ecosystem impacts are however distinct, with nitrogen more implicated in marine eutrophication and phosphorus a key driver of freshwater eutrophication. Only nitrogen is considered in this study. An updated nitrogen boundary includes only nitrogen fixation arising from fertiliser use, and is set at 69 teragrams of nitrogen (TgN) (Springmann et al., 2018). In estimating baseline nitrogen mobilisation for the livestock sector and food system, we adopt global estimates from Davis et al. (2016).

2.2.3. Land system change

The land-system change boundary refers to deforestation, that is, cleared forest as a percentage of pre-industrial cover. The boundary is set at 25%, which represents a weighted average of separate biome-level deforestation boundaries for tropical, temperate and boreal forest (Steffen et al., 2015). Pre-industrial forest cover is estimated at 55.3 million square kilometres (Mkm^2) (Bajželj et al., 2014; Ramankutty et al., 2008). In absolute terms, the boundary is therefore set at 13.9 Mkm^2 of deforestation. Land-system change for the food system is represented by total cropland and pasture occupying previously forested lands, as defined by Bajželj et al. (2014). 100% of pasture and 40% of cropland area is allocated to the livestock sector, with the latter representing that portion of cropland area globally used for growing feed (Mottet et al., 2017). Feedcrops are deemed to have displaced forests at the same ratio as food and energy crops, that is, 48% (Bajželj et al., 2014). This is considered a conservative assumption given that between 1990 and 2008, soybean and maize crops, two primary crops used for producing livestock feed globally, were leading individual drivers of deforestation globally (Cuypers et al., 2013).

2.3. Future scenarios

Baseline impacts are projected forward to 2050 in two future scenarios. The first, a reference scenario (REF), seeks to couple current impacts per unit of output with future population and food production projections. The second scenario, mitigation by efficiency (MBE), incorporates gains in resource-use efficiency primarily gained by closing the gap between the most and least efficient producing regions globally.

Production figures in 2050 upon which our GHG emissions and nitrogen mobilisation projections are based couple average production figures from 2005 to 2007 for different livestock commodities (FAOSTAT, 2018) with projected annual rates of change figures from 2005 to 7 to 2050 (Alexandratos and Bruinsma, 2012). Published rate of change figures are aggregated regionally based on developmental level. As several regions feature a combination of developed and developing nations, rate of change figures are weighted based on the number of people within each region living in a country classified as developed or developing (UN, 2014). Transition economies are classified as developed for this purpose, in line with the methodology adopted by the FAO (Alexandratos and Bruinsma, 2012). Additionally, published rate of change figures assume a global population of 9.15 billion in accordance with the UN's 2008 population revision. Calculated regional production figures have therefore been adjusted based on an updated global population projection of 9.6 billion from the UN's 2012 revision (UN, 2009; UN, 2013, see Table A1). Land-system change impacts are based on modeling work from Bajželj et al. (2014), which feature projections for the future expansion of cropland and pasture area in 2050 under various scenarios. All scenarios are based on changes in consumption from the FAO (Alexandratos and Bruinsma, 2012) coupled with population forecasts in the UN's 2012 revision (UN, 2013). These assumptions therefore align with those underpinning GHG emission and nitrogen mobilisation projections as described above. With the exception of the use of regional production forecasts and GHG emission factors, the analysis is conducted at the global level. Table 2 summarizes literature used to define REF and MBE values, as described below.

2.3.1. Climate change

A regional analysis of GHG emissions has been conducted using data

Table 2
Literature used to define 2050 REF and MBE values.

Domain	2050 values
Climate change	Production projections based on Alexandratos & Bruinsma coupled with the UN's 2012 population revision. Emission factors from FAO (2017a).
Nitrogen mobilisation	Production projections based on Alexandratos & Bruinsma coupled with the UN's 2012 population revision. Nitrogen intensity estimates from Davis et al. (2016)
Land-system change	Production projections based on Alexandratos & Bruinsma coupled with the UN's 2012 population revision. Agricultural expansion estimates from Bajželj et al. (2014)

from the FAO's GLEAM model (FAO, 2017a), which incorporates a global life-cycle assessment for defining emissions. Emissions from land-use change are omitted from this analysis. Emission factors are calculated based on regional emission estimates from GLEAM and production figures from 2010 (FAOSTAT, 2018, see Table A2). Emission factors from 2010 are retained for 2050 in the REF scenario, and therefore incorporate no efficiency gains. MBE emission factors assume mitigation of between 10% and 50%, determined as follows: (a) GHG emission factors in the most efficient region for a particular commodity improves by 10%; (b) the remaining emission gap between less efficient producing regions closes by 50%. This is consistent with the methodology adopted by Gerber et al. (2013), which focuses on the closure of emission gaps between the most and least efficient producers globally (see Tables A7 and A8).

2.3.2. Nitrogen mobilisation

Nitrogen mobilisation for the livestock sector in the REF and MBE scenarios is held to be a function of livestock production (as calculated via the method described in 2.3.1) and global weighted average nitrogen intensity figures from Davis et al. (2016). Nitrogen intensities are calculated based on the ratio of synthetic nitrogen applied to an area and the crop production of that area. It is assumed that all anthropogenic nitrogen inputs reach the environment, and are not recycled (Davis et al., 2016). The REF scenario assumes a global weighted average soil N uptake efficiency is 53%, in line with a global estimate by Bodirsky et al. (2014). For the MBE scenario, global soil N uptake efficiency increases to 75% in line with Bodirsky et al.'s Efficient Fertilisation scenario. This outcome would result in relative N losses being effectively halved (Bodirsky et al., 2014), and therefore represents an optimistic mitigation pathway (see Table A10).

2.3.3. Land-system change

Additional deforestation between 2009 and 2050 is based on projected agricultural expansion in the Current Trends (CT) and Yield Gains (YG) scenarios from Bajželj et al. (2014). CT is adopted for the REF scenario, and assumes yields in each global region will continue to increase linearly at current rates. YG is adopted for the MBE scenario, and assumes the sustainable intensification of production achieves yield gap closures in all regions (Bajželj et al., 2014). With limited data available on the proportion of new croplands likely be used for growing feed, the historical feedcrop proportion of 40% is adopted (Mottet et al., 2017). This is considered a conservative estimate given the projected per-capita increase in meat production, the majority of which will be met by industrial production methods that rely on feed from the world's croplands (Steinfeld et al., 2006). Of that projected agricultural expansion allocated to the livestock sector, 48% of feedcrop land and 18% of pasture is deemed to displace forests in line with the proportion of historical croplands and pasture that occupy previously forested lands (Bajželj et al., 2014) (see Table A11). This is deemed a conservative estimate given that two-thirds of land currently not being used for agricultural production or human settlements, but being suitable for cultivation, is covered in forest (Bajželj et al., 2014).

2.4. Mitigation potential of a consumption taxation

A primary goal of this study is to quantify the extent to which measures that can foreseeably be expected to emerge from a neoclassical economic framework can mitigate the sector's environmental impacts. The MBE scenario as described thus far under-represents this perspective, as it has not considered the mitigation potential of prices that more fully capture relevant environmental costs. Prices can promote this end via two means; first, by inducing technological change and subsequent gains in resource-use efficiency. Second, by triggering a demand response. While the MBE scenario seeks to capture realistically achievable mitigation from gains in resource efficiency, the additional mitigating effect of a tax in terms of its demand response is considered below. This analysis is undertaken for GHG emissions and nitrogen mobilisation, and coupled with the results of the REF and MBE scenarios for two further tax (TAX) scenarios. For each livestock commodity, the tax is levied based on the GHG emission factors relevant to that commodity's production. A tax of $171 per tonne CO_2eq (USD_{2005}) is chosen, being the mean value of five pricing models whose emission pathway is consistent with limiting global warming to 2 degrees Celsius in line with RCP 2.6 (CPLC, 2017) (see Table A12). Livestock commodity prices and elasticity of demand figures are calculated based on the analysis by Springmann et al. (2016a) (see Table A13). Projected changes in demand are deemed to flow directly to changes in production, and are coupled with emission factors and nitrogen intensity figures in the REF and MBE scenarios to estimate the sector's aggregate emissions and nitrogen mobilisation under this TAX scenario.

3. Results

3.1. REF and MBE scenarios

The livestock sector is estimated to account for 6.8 $GtCO_2$eq emissions, 63 TgN and 8.2 Mkm^2 of deforestation for the respective baseline years (see Tables A5, A10). These compare to total food system impacts of 9.5 $GtCO_2$eq (FAO, 2017b), 129 TgN (Davis et al., 2016) and 12.7 Mkm^2 of deforestation. Baseline impacts for the livestock sector as a proportion of total food system impacts, as well as its relative contribution to food consumed globally, are summarised in Fig. 1.

GHG emissions for the livestock sector in the REF scenario are projected to increase to 12.1 $GtCO_2$eq in 2050, a level at which the sector would occupy 60% of humanity's allowable GHG emission budget. Emissions are projected to reduce to 7.9 $GtCO_2$eq in the MBE scenario, shrinking livestock's planetary boundary occupation to 39%. Ruminant meat and milk production drive the sector's impacts in both scenarios, occupying 48% and 33% of the emission budget respectively. When the livestock sector's impacts are compared to the downscaled emission budget of 4.7 $GtCO_2$eq for agricultural non-CO_2 emissions only (Springmann et al., 2018), the planetary boundary value is transgressed even in the optimistic MBE scenario (see Table A9). Nitrogen mobilisation in the REF scenario is projected to increase to 105 TgN in 2050, a value that surpasses the planetary boundary value by 50%. This would reduce to 74 TgN in the MBE scenario, a point at which the sector

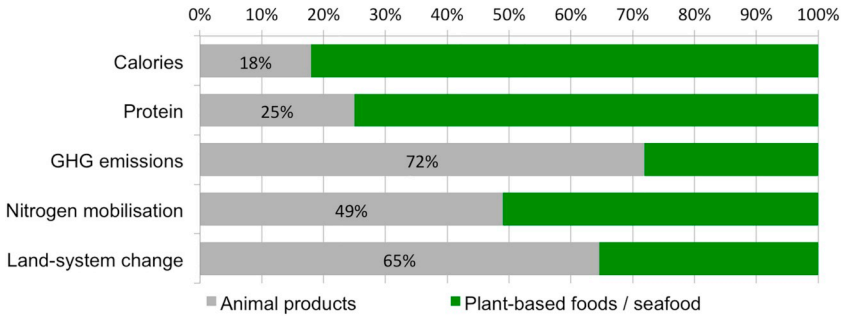

Fig. 1. Livestock's relative contribution to food consumed and anthropogenic impacts of food production globally.
(Sources: Calories and protein consumed estimates from Mottet et al., 2017. GHG emission estimates from FAO, 2017a, 2017b. Nitrogen mobilisation estimates from Davis et al., 2016. Land-system change estimates based on the authors' calculations as represented in Table A11 using data from Bajželj et al., 2014).

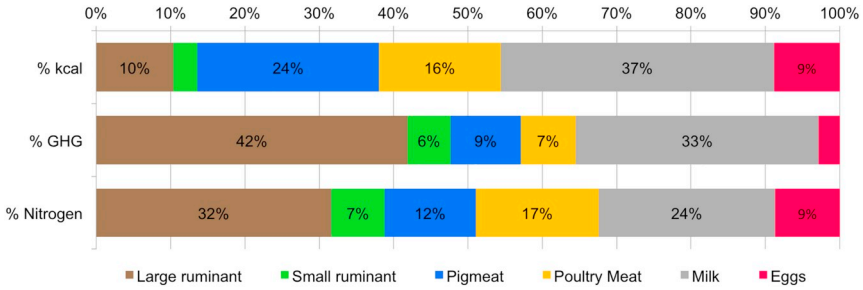

Fig. 2. Relative contribution of six main animal product categories to total animal-derived calories consumed and environmental impacts of livestock production globally in 2050. Results are depicted for the MBE scenario. (Sources: production forecasts based on authors' own calculations, as described in Section 2.3; GHG and nitrogen intensity figures are from FAO, 2017a and Davis et al., 2016, respectively).

would occupy 107% of the planetary boundary (see Table A10). The production of ruminant meat is particularly impactful with respect to both GHG emissions and nitrogen mobilisation, contributing 14% of the sector's calories consumed but causing 40–50% of impacts. Although milk production is similarly impactful in absolute terms it makes greater contributions to food consumed globally, accounting for 37% of total livestock calories consumed (see Fig. 2).

For land-system change, feedcrop and pasture area is projected to expand to 8.9 Mkm^2 and 37.1 Mkm^2 respectively in the REF scenario (Bajželj et al., 2014). On the assumption that 48% of feedcrop area and 18% of pasture area will continue to occupy previously forested lands in 2050, the livestock sector's boundary occupation in the REF scenario would expand to 80%. For the MBE scenario, total feedcrop and pasture area is projected to expand slightly to 6.6 and 37.3 Mkm^2 respectively to occupy 10.1 Mkm^2 of previously forested lands. Under this scenario the livestock sector would occupy 73% of humanity's safe operating space. Ruminant production occupies just over half of the land-system boundary in isolation (see Table A11).

3.2. TAX scenarios

With the introduction of a US$171 tax on CO_2eq emissions, aggregate meat demand in 2050 is forecast to reduce from 476 to 409 million tonnes. This represents a decline of 14%. Ruminant meat accounts for three-quarters of reduced meat demand, as a function of its higher emission intensity and concomitant larger shift in price resulting from the tax. Based on such changes in demand, the sector's GHG emissions would decline to 8.9 $GtCO_2$eq in the REF-TAX scenario, and 6.7 $GtCO_2$eq in the MBE-TAX scenario. The MBE-TAX value represents a 45% reduction from REF impacts, and would shrink the sector's allowable emissions space occupation to one-third. The projected change in global production reduces nitrogen mobilisation in the REF-TAX scenario to 83 TgN, and 64 TgN in the MBE-TAX scenario. With the combined mitigation potential of efficiency gains and the introduction of a tax, the sector's occupation of the nitrogen mobilisation boundary reduces to 93% (see Table A13).

3.3. Summary of results

Results for each domain and scenario are presented Table 3, with those values represented in relative to planetary boundaries in Fig. 3.

4. Discussion

4.1. Comparison to other studies

Six studies project direct agricultural GHG emissions for the livestock sector in 2050 under various iterations of a 'business as usual' scenario. Emissions from these analyses range from 8.2 to 14 $GtCO_2$eq. Our REF estimate for direct agricultural emissions of 9.8 $GtCO_2$eq falls within this range (see Table A9). Pelletier and Tyedmers (2010) and Davis et al. (2016) both provide estimates of nitrogen mobilisation from fertiliser that fall 3% of our estimate, although it is the latter study that our nitrogen intensity figures are based (variation in the 2050 projection is based on different production forecasts). Estimated crop and pasture land area for 2050 from Bajželj et al. (2014), from which our deforestation estimates are derived, are approximately in line with other estimates in the literature. These results are summarised in Table 4.

For livestock's mitigation potential, the analysis by Gerber et al. (2013) calculated that a 30% reduction in emissions would be attainable by closing the emission gap between the most and least efficient producers globally. This estimate compares well to the 34% reduction in emissions in the MBE scenario when compared to REF emissions. For the two tax scenarios, the demand response results in reduced total emissions of 26% and 16% for the REF and MBE scenarios (45% when this demand response is combined with MBE's efficiency measures). This compares to emission reductions for the livestock sector of 12% and 24% in Springmann et al. (2016a), resulting from the introduction of an emission price of $52 and $156 per tonne of CO_2eq.

4.2. Policy implications

The analysis thus far has not sought to answer the normative question of how much ecological space a food system (and livestock sector as a subset) tasked with meeting humanity's caloric and nutritional needs, and food preferences, should occupy. Seeking to quantify this is fraught with difficulty, given the complexities of the global economy and the value judgements such an undertaking would require. This may be particularly relevant to climate change, a domain to which the food system contributes approximately one-quarter of total emissions but where significant future mitigation is required. Given these complexities, the market may ultimately be the best mechanism for designating what portion of humanity's safe operating space the food system can sustainably occupy. This however relies on the right market mechanisms being in place, that is, mechanisms that constrain total anthropogenic impacts to a sustainable level (Daly, 1992; Costanza

Table 3
Summary of baseline and 2050 REF/MBE impacts.

Domain	Unit	Baseline	REF	MBE	MBE-TAX	% Δ from REF
GHG emissions	$GtCO_2$eq	6.8	12.1	7.9	6.7	45%
Nitrogen mobilisation	TgN	63	105	74	64	39%
Land-system change	Mkm^2	8.2	11.1	10.1		9%

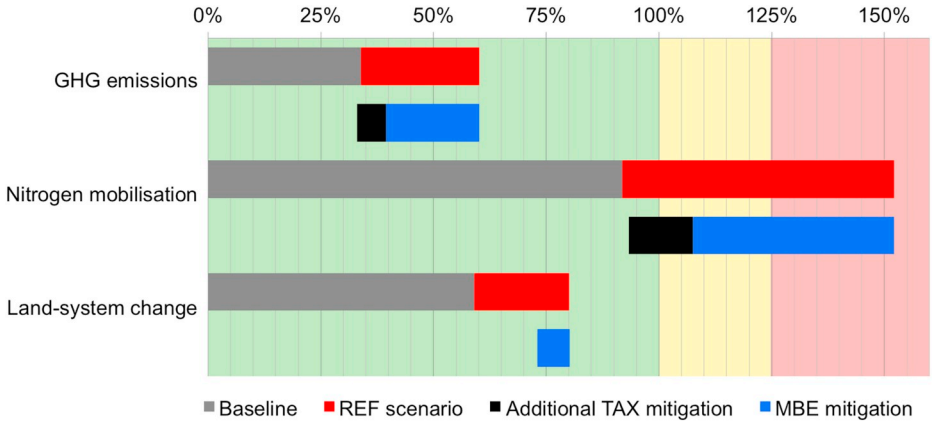

Fig. 3. Summary of impacts and mitigation potential relative to planetary boundaries. Safe operating space in each domain is represented by the green segment, while the yellow and red segments correspond to the zone of uncertainty and the zone of exceedance respectively. REF impacts in each domain are represented by the red bars. Blue and grey bars in the MBE and MBE-TAX scenarios represent total mitigation potential from REF impacts. All results are as per those described in 3.1 and 3.2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Comparison of REF values with 'business as usual' projections.

Article	Domain	Value	Unit
Pelletier and Tyedmers (2010)	GHG emissions	8.2	$GtCO_2eq$
Springmann et al. (2016b)	GHG emissions	8.3	$GtCO_2eq$
This study - REF	GHG emissions	9.8	$GtCO_2eq$
Revell (2015)	GHG emissions	9.8	$GtCO_2eq$
Davis et al. (2016)	GHG emissions	9.9	$GtCO_2eq$
Hedenus et al. (2014)	GHG emissions	10.0	$GtCO_2eq$
Pradhan et al. (2013)	GHG emissions	14.0	$GtCO_2eq$
Pelletier and Tyedmers (2010)	Nitrogen fertiliser	102	TgN
This study - REF	Nitrogen fertiliser	105	TgN
Davis et al. (2016)[a]	Nitrogen fertiliser	108	TgN
Bajželj et al. (2014)[a]	Total cropland	22.2	Mkm^2
	Total pasture	37.7	Mkm^2
Conijn et al. (2018)	Total cropland	23.8	Mkm^2
	Total pasture	58.9	Mkm^2
Röös et al., 2017	Total cropland	27.7	Mkm^2
	Total pasture	35.7	Mkm^2
Heck et al. (2018)	Total cropland	21.6	Mkm^2
	Total pasture	34.1	Mkm^2
Stehfest et al. (2009)	Total cropland	17.8	Mkm^2
	Total pasture	32.5	Mkm^2

[a] Values used underpin this study's projections.

et al., 1997).

Ecological economists tend to be sceptical of the view that a mechanism to promote this end can emerge from the market merely as a function of the profit objective and its promotion of resource efficiency. Accordingly, they endorse a scale-based approach to environmental governance (Pelletier, 2010) as a means of constraining the production and consumption of resources that drive anthropogenic impacts to a sustainable level. Such a policy would necessarily be external to the market (Daly, 2007), and may be similar to existing cap and trade systems where permits are distributed to producers and traded in the market (Tietenberg, 2003). The potential utility of this approach is not restricted to the food system, with its scope ideally covering all sectors that drive anthropogenic impacts. It should therefore be harmonised with any existing or future policies, particularly those focusing on limiting GHG emissions in the energy and transportation sectors. Planetary boundaries may serve as an ideal framework for such a policy, informing the environmental domains to which it applies and the caps on anthropogenic impacts (and resources that drive impacts) that are sustainable. 'Correct' supply prices of those resources that drive anthropogenic impacts would thus be an emergent property of the market, established by the interaction of the demand for, and supply of, permits (Tietenberg, 2010). For such pricing signals to function optimally, it is important too for existing subsidy regimes that distort pricing signals to be modified.

A policy measure of this nature would likely cause the price of animal products to rise in both absolute and relative terms, given the sector's high anthropogenic impacts in relation to its contribution to overall food security and economic output. This may serve an important dual end of promoting sustainable consumption practices while maintaining (and perhaps enhancing) producers' incentive to pursue gains in resource-use efficiency (Daly, 2007). Both these outcomes are likely necessary to a sustainable livestock sector, and food system more generally (Herrero et al., 2016; Hubeau et al., 2017; Poore and Nemecek, 2018). Modeling suggests that patterns of demand are responsive to such price changes, with a tax levied on food commodities based on their emissions predicted to reduce overall animal product demand while causing shifts toward those commodities with lower emission factors (Springmann et al., 2016a; Wirsenius et al., 2011). It is important that any such moderating effect be targeted at discretionary consumption in more developed parts of the world in order to preclude any undesirable outcomes, such as preventing populations in the least developed parts of the world from accessing moderate levels of animal products. For such populations, animal products contribute vital nutrients and are still an essential means of reducing diseases of undernutrition.

The role of macroeconomic policy may be particularly important to the promotion of sustainable consumption practices given the historical "meatification" (Weis, 2013, p. 67) of diets (and high consumption of discretionary foods more generally, see Hadjikakou, 2017). This phenomenon is tightly coupled with modernisation and economic growth, and thus broadly portrayed as a demand response to increasing affluence (Delgado et al., 1999; Steinfeld et al., 2006). Some have conjectured however that there is an important supply-driven component that is often ignored, resulting from a combination of supply increments and cost externalisation (Rivera-Ferre, 2009). Externalities may be evident not only with respect to the sector's environmental burdens as detailed above, but also animal welfare (McInerney, 1993) and public health (Tilman and Clark, 2014). It is likely therefore that such factors have contributed to the historical decline in the price of animal products, both in real terms and relative to fruits and vegetables, and the continued adoption of diets high in animal protein (Rivera-Ferre, 2009; Wiggins et al., 2015).

4.3. Transformations in consumption and production practices

A well-established body of research attests to the utility of dietary change as a means of mitigating food-related environmental impacts (Goodland, 1997; White, 2000). This case has been made for each of the four planetary boundary domains being transgressed; climate change (Springmann et al., 2016a; Röös et al., 2017; Herrero et al., 2016; Stehfest et al., 2009; Tilman and Clark, 2014), biogeochemical flows (Bodirsky et al., 2014; Metson et al., 2012), land-system change (Erb et al., 2016; Röös et al., 2017; Bajželj et al., 2014) and biosphere integrity (Machovina et al., 2015). The mitigation potential in each domain is generally a function of the proportion of calories derived from

animal and plant sources, with shifts from the former to the latter ceteris paribus having beneficial effects. Additionally, the substitution of ruminant with monogastric meat has been demonstrated to offer some mitigation potential, particularly with respect to GHG emissions (Tilman and Clark, 2014; Springmann et al., 2016a).

This substitution effect may however create additional pressure on other boundaries by stimulating demand for feedcrops grown from arable land. This is due to monogastric production systems having a higher reliance on these food-competing feed (FCF), the production of which drive the sector's nitrogen fertiliser use and have historically displaced forests at a higher rate than pasture (Bajželj et al., 2014). Additional demand for FCF may therefore create pressure on the nitrogen mobilisation and land-system change boundaries, with nitrogen fertiliser being necessary to achieving continued increases in yield gains and minimising agricultural expansion, but also a driver of harmful changes to biogeochemical cycles. This tension is exacerbated by the losses inherent to the process of converting feed calories into animal products (Tilman and Clark, 2014; Schader et al., 2015; Van Zanten et al., 2018), and therefore cannot easily be resolved when mitigation solutions focus on production practices only and overall meat consumption remains high.

The substitution of animal products with plant-based protein sources on the other hand can relieve such tensions, as a function of their relatively low resource demands. It is posited here that an economic system where pricing signals facilitate the adherence to emission and resource budgets will likely induce this desirable substitution effect. This is due to the relatively high opportunity costs of those resources utilised for producing FCF, and the inefficiencies associated with converting those calories into animal products. The redirection of resources used for growing FCF could therefore represent a significant constraint on livestock production. In a scenario where the practice of producing FCF is fully eliminated, Schader et al. (2015) estimate that approximately 5% of global calories could be derived from terrestrial animal sources. Under this scenario, as well as incremental steps in that direction, anthropogenic impacts of the livestock sector are mitigated across each of the domains included in this analysis (Schader et al., 2014).

With constraints on feed resource availability, it is envisaged that remaining livestock production would largely emanate from those production systems that draw heavily on “ecological leftovers” (Garnett et al., 2017), or low opportunity cost resources. This includes food wastes, crop residues and non-arable land resources that are unsuitable for growing crops or establishing forests (Garnett et al., 2017; Schader et al., 2015; Van Zanten et al., 2018). This strategy would involve livestock shifting back to their more traditional role within the food system as “default land user(s)” (Steinfeld et al., 2006, p. 76), representing the only means by which these low opportunity cost resources can be harnessed within the food system. While this may in some instances favour ruminant animals due to their unique physiology that allows them to digest grass, constraints will arise as a result from their relatively high direct emissions and land requirements. Within this paradigm, the production of different livestock commodities in different production systems would thus continue only to a point where the marginal costs of production (in economic and environmental terms) remain low enough so as to allow remaining food calories to be produced without breaching emission and resource budgets.

4.4. Study limitations and uncertainty

This study has sought to quantify the future trajectory of livestock's environmental impacts in two primary scenarios, REF and MBE. MBE aligns with a neoclassical approach to sustainability that seeks fundamentally to optimise efficiency as a means of reducing impacts per unit of output. One limitation of the methodology adopted here is its exclusion of potentially paradigm-shifting technologies. This includes carbon storage technologies and in vitro meat, both of which are subject to technological uncertainties, while the latter is subject to additional uncertainty with respect to consumer acceptance (Bekker et al., 2017; Goldstein et al., 2017).

There are several sources of uncertainty impacting our estimates, and their relationship to biophysical constraints that may exist in the Earth system. In defining planetary boundary values, relevant literature includes an upper and lower bound reflecting a ‘zone of uncertainty’ for each domain. These ranges are 16.5 to 23.8 $GtCO_2eq$ for climate change (Rogelj et al., 2011), 52 to 113 TgN for nitrogen mobilisation (Springmann et al., 2018) and 13.8 to 25.5 Mkm^2 for land-system change (Steffen et al., 2015). Utilising these upper or lower boundaries would materially change livestock's operating space occupation; 25–51% for GHG emissions, 66–143% for nitrogen mobilisation and 40–73% for land-system change.

A further limitation relates to adopting a global framework for assessing the sustainability or otherwise of anthropogenic impacts, which may ignore potentially important lower-scale regional boundaries or thresholds. This is relevant to those domains with high spatial heterogeneity such as nutrient loading and land use (Kummu et al., 2017). Global boundaries should be considered complimentary to local environmental thresholds, as they can still highlight areas of priority for global environmental governance (Springmann et al., 2018; Heck et al., 2018; Conijn et al., 2018). Efforts to reconcile local thresholds with global boundaries is an ongoing area of research, and one that is important to the operationalisation of the planetary boundaries concept (Gerten et al., 2013).

Our 2050 estimates are subject to a number of uncertainties. Impacts are summarised in each domain independently, and therefore the dynamics between impacts across domains are not factored into our analysis. Our climate change estimates omit land-use change emissions, as we found no reliable means of projecting such emissions forward to 2050. This likely under-represents the livestock sector's future emissions given the scale of current emissions from this source, although pasture can in some circumstances act as a net carbon sink (Doran-Browne et al., 2017). For the biogeochemical flows boundary, our analysis excludes phosphorus and therefore does not fully capture livestock's impacts in this domain.

Our TAX scenarios are subject to the following limitations. First, the analysis is conducted at the global level using a static model that does not incorporate potential dynamic effects from the introduction of the taxation, such as shifts in production between regions or changing consumer preferences. Second, the level of the emission tax chosen is based on Shared Socioeconomic Pathway 2, and may not align with the socioeconomic assumptions underpinning 2050 estimates as described in Section 2.3. Third, the tax seeks only to internalise environmental costs related to GHG emissions, and therefore excludes other domains within the planetary boundaries framework. It may therefore underrepresent the utility of a policy measure that seeks to internalise the cost of environmental impacts within the price of food commodities, in terms of the demand response such a policy might trigger. And fourth, the land-system change is excluded from the TAX scenario due to the difficulties in projecting how marginal changes in demand may impact forests specifically. Despite these shortcomings, our results are well within the range of previous estimates in the literature and provide clear evidence of the need for changes in both consumption and production practices if anthropogenic impacts of food production are to return to a sustainable level.

5. Conclusion

The livestock sector currently occupies a significant portion of humanity's safe operating space with respect to climate change, biogeochemical flows and land-system change. The current trajectory of animal product consumption is thus highly problematic in a sustainability sense, presenting an urgent need to decouple the adoption of diets high in animal products with the aspirations of a growing global middle

class. Based on optimistic estimates of the potential mitigation extent arising from efficiency gains and taxation of animal products, it is consequently suggested here that bold macroeconomic policies that incorporate a scale-based approach to environmental governance offer a promising and arguably necessary means of promoting this end. By constraining macroeconomic scale, producers and consumers are both incentivised to adopt practices whose biophysical effects align with a sustainable macroeconomic scale. This study has sought to demonstrate that both production- and consumption- based interventions are essential to the achievement of a sustainable food system, with the pricing system deemed to be a necessary conduit between producers and consumers, and the planetary boundaries that define humanity's safe operating space.

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Appendix A. Supplementary data

Supplementary data to this article containing all underlying data and calculations can be found online at https://doi.org/10.1016/j.ecolecon.2019.01.033.

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